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EXPLOSION-PROTECTED TECHNOLOGICAL EQUIPMENT - UNCERTAINTY CONSIDERATIONS IN TEMPERATURE MEASUREMENT TESTS

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Abstract: *In the context of explosion protection of technological equipment in general and electrical equipment in particular, the paper estimates the uncertainty involved in measuring the maximum surface temperature for intrinsically safe and increased safety types of protection. Equivalent test scenarios have been considered, using different sensor application methods. The context of the work is presented in the first part. The second part presents the stand used for temperature tests and the theoretical model adopted for heat exchange. In the third part of the paper, the obtained results are presented and discussed. Based on the results, it is concluded that the uncertainty of temperature measurement is influenced by the test conditions and the way the temperature sensors are applied.*
Keywords: *temperature testing, uncertainty estimation, technological equipment, explosive atmospheres, explosion risk.*

1. INTRODUCTION

Current trends in the development of technological equipment aim to increase efficiency, safety, and environmental compatibility by increasing the degree of functional integration and intelligence implemented in the systems designed to coordinate processes. On the other hand, current trends in the implementation of clean technologies involve the use of hydrogen as an energy carrier. This leads to the risk of explosion with the use of technological equipment. Although the risk of hydrogen explosion is no longer a novel element in the context of the use of technological equipment, the magnitude predicted by current trends requires further attention.

In technological equipment and systems, flammable substances, depending on the specifics of the technology, can be found both at the input part of the process and during or at the end of the process. The presence of these substances gives rise to special potentially explosive atmospheres. [1].

The economic context of the European area implies a common, free market in which the transfer from the manufacturer to the user of technological equipment intended for use in processes with explosion hazards is regulated by the ATEX Directive. [2]. Its requirements lay down generic explosion protection characteristics by the specific features of potentially explosive atmospheres. In this context, equipment categories (1, 2 and 3 G/D) should be mentioned as being compatible with explosion hazardous zones 0, 1 and 2 for explosive gases, vapors, and mists, respectively 20, 21, 22 for flammable dusts, flyings and fibers.

The technical implementation, at detailed, of these generic requirements is carried out by taking into account the requirements laid down in the specific standards. [3].

The particularities of the implementation of the technical requirements lead to so-called "explosion protection types". Although each type of protection has certain particularities, the actual implementation of explosion protection is often based on limiting the energy transferred to the explosive atmosphere by sparks. [4], but also by heated surfaces. The sources of these manifestations are various, such as mechanical, electrical, ultrasonic, exothermic reactions, hot surfaces, electromagnetic fields, static electricity, etc.

The implementation of technological equipment categories is based on providing explosion protection with consideration of different failure scenarios. At the International Electrotechnical Committee, as an alternative to the ATEX categories, is the level of protection of the equipment (G/D a, b, c).

2. PROBLEM DESCRIPTION

In the technological and functional context, at least half of the input parameters in control processes are temperatures. The importance of evaluating the uncertainty of temperature measurement is due to the fact that some measured values may approach the accepted thresholds. [5] and [6]

A situation frequently encountered in practice is that of hot surfaces as an explosion risk factor. Thus, surfaces in contact with explosive atmospheres can lead to an explosion hazard if the temperatures specific to the temperature classes of flammable substances (from the auto-ignition temperature point of view) are exceeded.

From the point of view of explosion protection, the temperature of surfaces that may come into contact with the explosive atmosphere must also be limited. [7] Confirmation of compliance with this requirement is carried out at the testing stage of the technological equipment, and in the testing process, the determination of the temperature involves ranges of uncertainty. The value of these uncertainties becomes even more important as the values of the measured temperatures approach the limit thresholds allowed by the reference standard. [8] and [9]

The process of temperature measurement involves a heat transfer from the surface to be measured to the sensor of the measurement system, but in this measurement scenario, there are also the influences induced by the environment and the application conditions of the sensor. In this paper, the evaluation of the measurement uncertainty is considered, focusing on the measured surface temperature.

The parameters considered when estimating the temperature measurement uncertainty are: the sensor attachment method and the dimensions of the elements characterizing this attachment. The attachment methods considered are: bay using thermally conductive paste and thermally conductive fixing tape and paste.

3. RESEARCH STAGES

The aim of the work, in the first step of the approach, is to define the geometry of the sensor attachment to the surface to be measured for both scenarios. The second step identifies the heat transfers characterizing each attachment scenario. Then the computational relationships characterizing the heat transfers are identified. In the fourth step, the ranges of values for the geometrical parameters characterizing the sensor attachment scenarios are chosen and the calculated values of the surface temperature measurement uncertainty are determined. In the last step, the obtained results are analyzed and the range of uncertainties resulting from the simulation method is compared with the range of uncertainties resulting from the GUM. [10] and [11]

4. METHODS USED

To determine the uncertainty of the temperature measurement it is necessary to evaluate the heat exchange in the chosen scenario and with the applied measurement means.

Basically, the measurement process involves the application of a temperature sensor to the surface area to be measured. In a preliminary step, which may involve a thermo-vision camera, the location of the sensor can be established and identified.

Sensors commonly used for temperature measurement are based on K or J-type thermocouples.

The theoretical model, based on the heat exchange balance, must include the surface to be measured (as heat source), the environment (as heat destination), the sensor, and the attachment means (as conduction means).

To identify the maximum temperature values of the surfaces of the technological equipment, which may come into contact with the explosive atmosphere, the scenarios considered are those in which the heat exchange with the environment is lower. As a result, for the current analysis, the scenario of a horizontally placed measuring surface was considered. This is in direct contact with the ambient air and transfers heat to the environment only by convection. This heat transfer process is influenced by the presence of the temperature-measuring sensor and the means of attaching/fixing it to the surface.

Since the analysis is focused on the evaluation of the measurement uncertainty by using an applied sensor, for the present stage it is considered that the temperature of the surface to be measured is uninfluenced by the measurement.

The temperature measurement is performed relative to ambient temperature; therefore, an ambient temperature sensor is also used.

The observed temperature dynamics in previous measurements allow a time interval of one second for the acquisition of temperature values.

In order to determine the measurement uncertainty introduced by the contact of the sensor with the measured surface and the scenario of its attachment to the surface, the geometry shown in Figure 1 was considered.

In scenario (*a*), the surface of the thermally conductive paste was considered to have the shape of a spherical calotte, defined by the parameter: height - *h* and diameter - *d*.

Similarly, in scenario (*b*), the parameters are the height of the attachment strip in front of the sensor and the thickness of the attachment strip.

The two temperature sensor application scenarios are shown in Figure *1*.

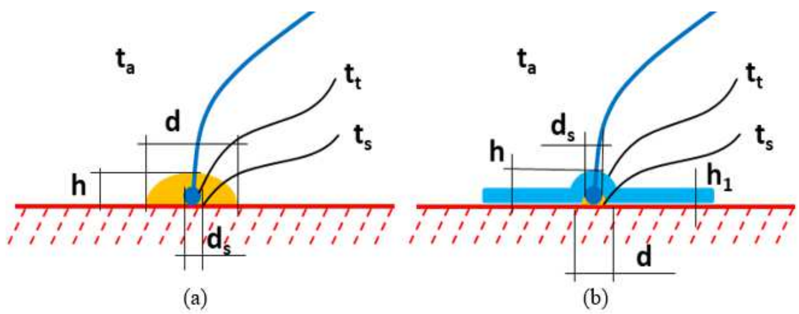

Fig. 1. Temperature sensor application scenarios (a - with thermally conductive paste, b - with fixing foil and thermally conductive paste).

For ease of mathematical modeling, it is assumed that the heat transfer to the environment between the heat-conducting paste and the fixing tape is characterized by the same convection flow as between the measuring surface and the environment without the measuring sensor.

In the configuration with the temperature sensor applied, the slightly larger surface area of the spherical calotte, made of thermally conductive paste or fixing tape, may cause a slight decrease in the measured temperature, and any variations in the dimensions of the spherical calotte will imply uncertainty in the temperature measurement.

By equations *1* through *4*, the heat balance between the measuring surface, the sensor, and the ambient environment was modeled. Due to the relatively small, but close to-sensor dimensions of the resulting spherical calotte, the temperature of the heat conducting paste respectively of the fixing band in the sensor area was assumed to be the same as the sensor temperature.

$$Q = k_t \cdot S_0 \cdot (t_s - t_a), Q = k_t \cdot S_1 \cdot (t_t - t_a). \qquad (1)$$

$$\frac{t_s - t_a}{S_1} = \frac{t_t - t_a}{S_0}. \qquad (2)$$

$$S_0 = \pi \cdot \left(\frac{d}{2}\right)^2, S_1 = \pi \cdot \left(\left(\frac{d}{2}\right)^2 + h^2\right). \quad (3)$$

$$t_s = k \cdot (t_t - t_a) + t_a, k = 1 + \frac{4h^2}{d^2}. \quad (4)$$

For the banding scenario, the same relationships are used taking into account, the height of the calotte, the thickness of the band - h1, and the diameter of the sensor - d_s, according to the relationship (5).

$$h = h_1 + d_s,\ d = h_1 + d_s,\ => k = 5. \quad (5)$$

For Equations (*1*) define the heat transferred from the measuring surface to the measuring assembly (sensor and fixture) and the heat transferred from the measuring assembly to the ambient. Considering that the two quantities of heat are approximately equal equation (*2*) is derived. To simplify the model, the equality of the proportionality coefficients in equation (*1*) has been considered.

For the evaluation of the d and h values, the diameter of the nozzle of the heat-conducting paste application, which has a value of 1.6 mm, and the diameter of the sensor alloy sphere, which has values between *1-1.3 mm*, were taken into account. The distribution range of the values was defined according to Figure *2*. To treat the covering case for the resulting uncertainty, all pairs of values were considered equiprobable, thus their distribution was uniform.

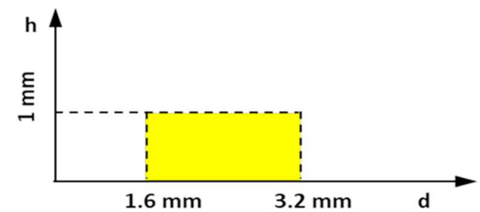

Fig. 2. Distribution of h and d parameter values.

$$t_a = t_{am} + \varepsilon_{ta}, t_t = t_{tc} + \varepsilon_{tc}. \quad (6)$$

$$h_{sensitivity} = \frac{\partial k}{\partial h} = \frac{8h}{d^2}, d_{sensitivity} = \frac{\partial k}{\partial d} = -\frac{8h^2}{d^3}. \quad (7)$$

$$u_s = \sqrt{\left(h_{sensitivity} \cdot u_h\right)^2 + \left(d_{sensitivity} \cdot u_d\right)^2 + (k \cdot u_{tc})^2 + (-k \cdot u_{am})^2} \quad (8)$$

In equation (*6*) the parameters ε_{ta} and ε_{tc} represent noises which also contribute to the measurement uncertainty. They are due to the ambient environment during the test, and their characterization is determined directly from the analysis of the measured values. The uncertainty introduced by the measured values t_{am} and t_{tc} are taken from the calibration certificates of the measurement system.

The parameters ta and t_t represent the calculated ambient temperature and the sensor temperature.

Equation (*7*) shows the values of the sensitivity coefficients for *h* and *d* dimensions.

The traditional approach is based on equation (*8*), by which the uncertainty of the surface temperature measurement is expressed, considering the two temperature measurement scenarios.

Due to the fact that in equation (4) there is a coefficient with nonlinear behavior, this nonlinearity induces an asymmetry in the distribution of the surface temperature values determined by the calculation. According to equation (*7*) a positive density skewness of the surface temperature values can be estimated.

For this reason, in the present work, the Monte Carlo method is used to determine the surface temperature uncertainty by simulation. For this purpose, *108* sets of parameters were generated as follows: for parameters h and d uniform distributions of values in the ranges prescribed in Figure *2* were chosen, and for the other parameters normal distributions with parameters resulting from the measurement process and from the calibration certificate of the measurement system were used.

5. RESULTS

Surface temperature measurement was performed for a primary galvanic element during short-circuit discharge. The measurement frequency was one measurement per second.

The temperature measured in the first step increased, then, as the electrochemical energy was exhausted, the temperature gradually decreased. The measurement process was maintained for another *70 seconds* after reaching the maximum value.

The diagram in Figure *3* shows the measured temperature and also the range of maximum values expressed in degree Celsius.

The average maximum temperature value recorded was *80.59°C*, with a variation characterized by a standard deviation of *0.583°C*.

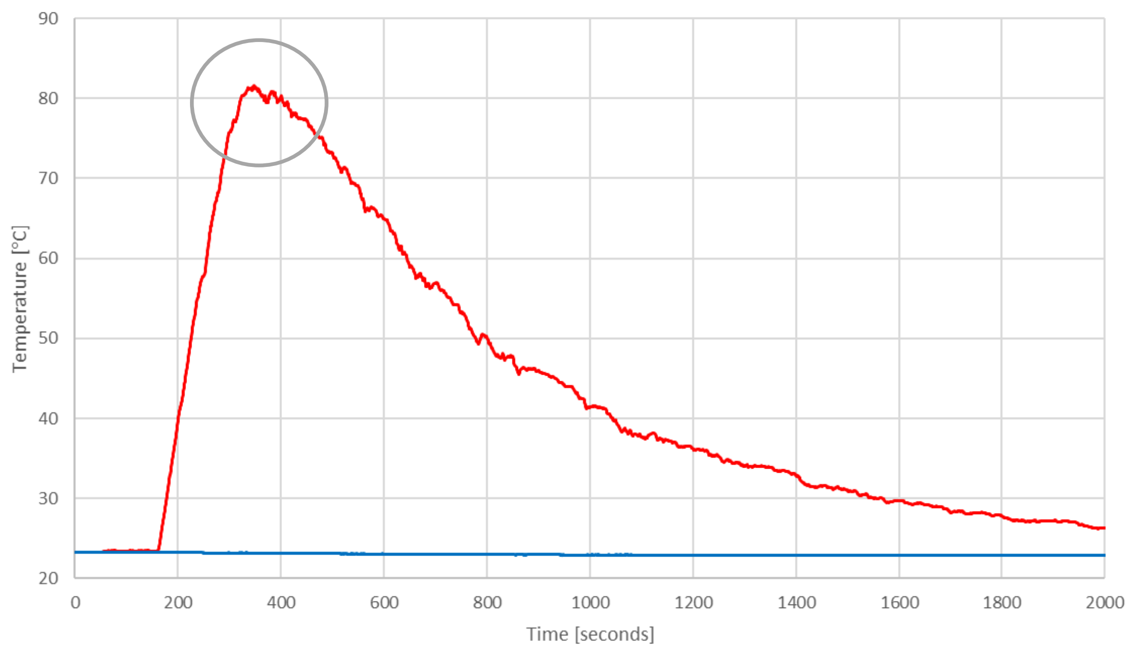

Fig. 3. Maximum values of the measured temperature for the surface of the galvanic element (red) and the ambient (blue).

The parameters presented in figure 1 and equations (6) are defined in Table 1 and those were taken into account to determine the temperature measurement uncertainty.

Table 1

Input parameters.

Nr.	Parameter	Values	Distribution
1.	h [mm]	min=0; max=1	uniform
2.	d [mm]	min=1.6; max=3.2	uniform
3.	ε_{ta} [°C]	mean=0; sigma=0.018	normal
4.	ε_{tc} [°C]	mean=0; sigma=0.0583	normal
5.	t_{tc} [°C]	mean=23.17; sigma=0.15	normal
6.	t_{am} [°C]	mean=80.59; sigma=0.15	normal

Following the application of the proposed model on the input data set, as shown in Table *1*, an asymmetric distribution with positive skewness for the calculated surface temperature values resulted.

The density distribution of the *108* values of temperature t_s, expressed in degree Celsius is plotted in Figure 4. Light blue represents the range containing *95%* of the most probable surface temperature values and orange represents the arithmetic mean value of the calculated surface temperature.

By sampling with different volumes of values, it was concluded that samples with at least *40* values preserve homoscedasticity of surface temperature values.

The calculated dispersion of the surface temperature values is *15.68 K*, compared to the mean value of *95.546°C*.

Considering the sample size with *40* values, the resulting arithmetic mean deviation is *2.479 K*. Using a coverage factor of *2* results in an uncertainty range of ±*4.959 K* and a confidence level of *97.7%*.

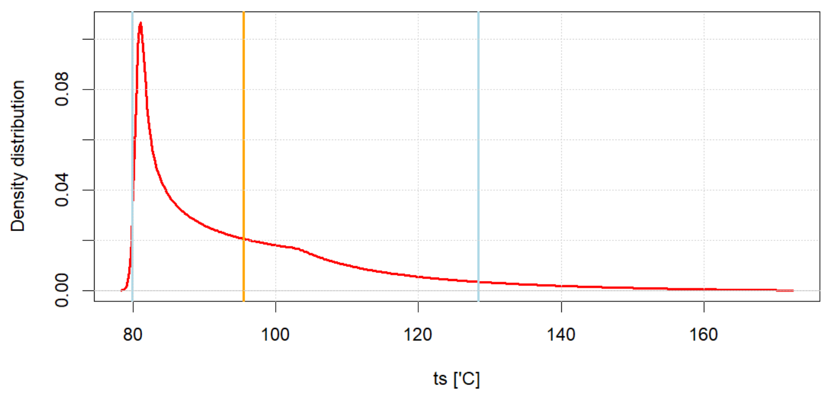

Fig. 4. Density distribution of calculated surface temperature (t_s *[°C]*) values.

This uncertainty value is close to reasonable values for temperature measurements and is one order of magnitude smaller than the value calculated according to GUM.

In this paper is proposed and investigated an alternative to GUM to address the nonlinearity induced by the equations of the employed physical model.

6. FURTHER RESEARCH

For the current approach, a simple, stationary scenario of the parameters influencing the measured value of the surface temperature was considered.

In the next steps, the influences of the variation of the parameters characterizing the thermal contact of the sensor with the measured surface can be identified.

Another appropriate approach is to take into account the dynamics of surface temperature variation caused by varying internal exothermal processes.

7. CONCLUSIONS

Although the input parameters used for the simulation process were characterized by the same distribution, dispersion, and mean as in the GUM method, using the method to determine the uncertainty of the surface temperature measurement uncertainty, the simulation resulted in values one order of magnitude lower than that based on GUM.

The heating processes of galvanic elements exposed to short-circuit faults can lead to temperature values that no longer allow classification in the T6 temperature class.

Due to the non-linear character of the calculated surface temperature, depending on the parameters characterizing the measured values and the thermal contact, the variation of some input parameters may strongly influence the uncertainty value of the surface temperature.

The scenario of fixing the sensor with an adhesive tape, based on the considered thermal model, proved to be a particular case of the method of applying the sensor on the surface with thermally conductive paste.

8. ACKNOWLEDGMENTS

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For performing the calculus R and R Studio was used [12] and [13].

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Echipament tehnologic protejat la explozie – considerații asupra incertitudinii la încercările de măsurare a temperaturii

În contextul protecției împotriva exploziilor a echipamentelor tehnologice în general și a echipamentelor electrice în special, lucrarea estimează incertitudinea implicată în măsurarea temperaturii maxime de suprafață pentru tipurile de protecție cu siguranță intrinsecă și cu siguranță sporită. Au fost luate în considerare scenarii de testare echivalente, utilizând diferite metode de aplicare a senzorilor. Contextul lucrării este prezentat în prima parte. A doua parte prezintă standul utilizat pentru testele de temperatură și modelul teoretic adoptat pentru schimbul de căldură. În a treia parte a lucrării, sunt prezentate și discutate rezultatele obținute. Pe baza rezultatelor, se concluzionează că incertitudinea măsurării temperaturii este influențată de condițiile de testare și de modul de aplicare a senzorilor de temperatură.

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